

Testing of a Miniature Loop Heat Pipe with Multiple Evaporators and Multiple Condensers for Space Applications

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Abstract

Thermal performance of a miniature loop heat pipe (MLHP) with two evaporators and two condensers is described. A comprehensive test program, including start-up, high power, low power, power cycle, and sink temperature cycle tests, has been executed at NASA Goddard Space Flight Center for potential space applications. Experimental data showed that the loop could start with heat loads as low as 2W. The loop operated stably with even and uneven evaporator heat loads, and even and uneven condenser sink temperatures. Heat load sharing between the two evaporators was also successfully demonstrated. The loop had a heat transport capability of 100W to 120W, and could recover from a dry-out by reducing the heat load to evaporators. Low power test results showed the loop could work stably for heat loads as low as 1W to each evaporator. Excellent adaptability of the MLHP to rapid changes of evaporator power and sink temperature were also demonstrated.

Key Words: Two-Phase Heat Transfer, Loop Heat Pipes, Multiple Evaporators, Multiple Condensers, Spacecraft Thermal Control

1. INTRODUCTION

A loop heat pipe (LHP) utilizes boiling and condensation of the working fluid for heat transfer and surface tension forces developed by the evaporator wick to circulate the fluid for heat transport [1,2]. It can transport large heat loads over long distances with small temperature gradients. LHPs have gained increasing acceptance for spacecraft thermal control, and are being used or to be used on several NASA spacecraft such as ICESAT, AURA, SWIFT and GOES and commercial communications satellites [3-6]. All these state-of-the-art LHPs have a single evaporator with capillary wicks of about 25mm outer diameter (O.D.).

As spacecraft become smaller, all spacecraft components, including the thermal subsystem, must be down sized. In addition, an LHP with multiple evaporators is highly desirable to accommodate multiple instruments or an instrument with a large thermal footprint [7-9].

Recently, a miniature LHP (MLHP) with has been developed at NASA Goddard Space Flight Center. The MLHP has following features:

1) Two miniature evaporators with 6.35mm O.D.

wicks

2) Two evaporators and two condensers in a single LHP

3) Thermoelectric converters (TECs) for temperature control and start-up success.

Comprehensive ground tests which included start-up, capillary limit, power cycle, sink temperature cycle, and their gravity dependences have been conducted in order to demonstrate following performances in one-G environment:

- 1) Stable operation of the MLHP
- 2) Reliable and repeatable MLHP start-up and shut down
- 3) MLHP operation when the two evaporators receive various heat loads (even and uneven heat loads)
- 4) Heat load sharing between the two evaporators
- 5) MLHP operation when the two condensers sinks are at different temperature
- 6) The ability of the TECs to control the compensation chamber (CC) temperature

In this paper, only the tests where no active CC temperature control was made will be presented. These tests were conducted to establish a baseline, so that the effectiveness of using the TEC for CC temperature control can be evaluated.

2. TEST ARTICLE AND TEST SETUP

Figure 1 shows the schematic of the MLHP test article, which consists of two parallel evaporators, two parallel condensers, a common vapor transport line and a common liquid return line. Each evaporator has its own integral CC. Main features of this MLHP include 1) 6.35-mm O.D. evaporator wicks; 2) Titanium primary wicks with 1.65 μm pore size; 3) Stainless steel vapor and liquid transport lines with 2.38 mm and 1.59 mm O.D., respectively; 4) Aluminum condensers with 2.38 mm O.D.; and 5) A thermoelectric cooler (TEC) attached to each CC. Copper thermal straps connect the rear side of the TEC to the evaporators. A flow regulator made of capillary wick with 10 micron pores is installed at the downstream of each condenser. The flow regulator prevents vapor from penetrating the wick before both condensers are fully utilized, and hence serve to balance the flows between the two condensers. The loop is charged with 29 grams of anhydrous ammonia. Table 1 shows the geometric parameters of the main components. A 400-gram aluminum mass was attached to each evaporator to simulate the instrument mass. A cartridge heater was attached to each thermal mass to provide heat loads between 1W and 150W per evaporator. Each condenser was attached to a cold plate; and each cooled was cooled by a separate chiller. Figure 2 shows the schematic of the test loop with thermocouple locations. Seventy-two (72) thermocouples are used to monitor the loop temperatures. A data acquisition system consisting of a data logger, a personal computer, a CRT monitor, and Labview software is used to monitor and store data. The data is updated on the monitor and stored in the computer every second.

3. TEST RESULTS

The following abbreviations are used in presenting the test data:

- E1 - Evaporator 1
- E2 - Evaporator 2
- CC1 - Compensation Chamber 1
- CC2 - Compensation Chamber 2
- C1 - Condenser 1
- C2 - Condenser 2

3-1 Overview of Test Results

To establish a baseline, the MLHP was first tested without TECs. An extensive test including start-up, high power, low power, power cycle, and sink temperature cycle tests with more than 250 hours of data was conducted. The loop demonstrated stable operation under all test conditions.

Successful start-ups were demonstrated with E1/E2

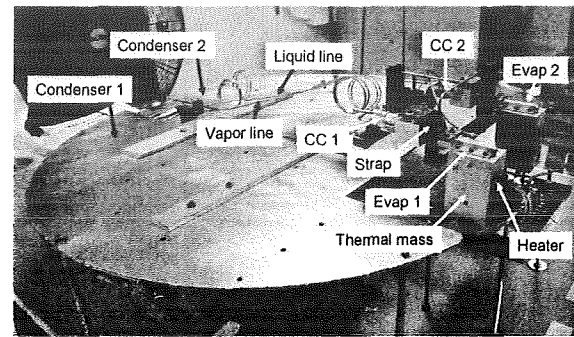


Figure 1. Photo of MLHP

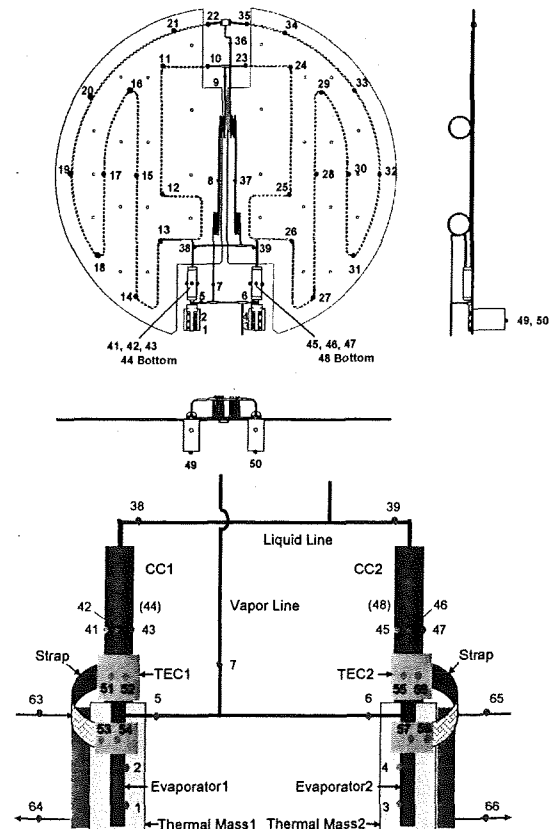


Figure 2. Thermocouple Location of MLHP

Table 1. Summary of Design Parameters

Evaporator	Aluminum 6061 9.65 mm O.D. x 52 mm L
Primary Wick	Titanium 6.35 mm O.D. x 3.18 mm I.D. 1.65 μm pore size 0.2 E-13 m ² Permeability
CC	SS 304 22.2 mm O.D. x 72.4 mm L
Vapor Line	2.38 mm O.D.
Liquid Line	1.59 mm O.D.
Condenser	2.38 mm O.D. x 2540 mm L
Working fluid	Ammonia 29 grams

heat loads from 1W/1W to 60W/60W to both evaporators, and to one evaporator only from 2W to 100W. Low power operation included 2W/0W, 0W/2W, and 1W/1W, while high power operation included 80W/80W, 110W/0W, and 0W/120W. The two evaporators were able to share heat loads automatically. Moreover, the evaporator switched between the evaporator mode and condenser mode of operation depending on the surrounding thermal environment. The heat transport capability of the loop was between 100W and 140W, depending on the evaporator heat load distribution and the operating temperature.

3-2 Start-up Test

An LHP must start successfully before it can transport a heat load. Start-up can be problematic in some cases and may require pre-conditioning, at low heat loads [1, 2]. The LHP start-up is characterized by an increase of the vapor line temperature to the CC saturation temperature and a decrease of the liquid line temperature, indicating that a flow circulation has been established. A start-up is successful if the flow circulation continues and the CC and the evaporator temperatures are steady, with the evaporator temperature slightly higher than that of the CC.

More than 90 start-up tests were conducted with a wide range of evaporator power and condenser sink temperature. The MLHP started successfully in all cases by simply applying a heat load to the evaporator without any pre-conditioning.

Figure 3 shows temperatures of the 1W/1W, 293K/293K start-up. Even at power as low as 1W/1W, this loop started successfully. At 8:34 a heat load of 1W/1W was applied to E1/E2. E1/E2 temperature began to increase, and, about 240 second later, loop started, as indicated by a drop of the liquid line temperature. After loop started, the CC temperature kept rising because the returned subcooling liquid was not enough to compensate for the heat leak from evaporators to CCs. The liquid line was parasitically heated by the ambient.

Figure 4 shows the loop temperature during the start-up with 2W/0W, 273K/273K. At 8:33 a heat load 2W was applied to E1. E1 temperature began to increase, and after 70 seconds, the loop started.

Figure 5 shows the temperature profiles during the start-up where 60W/60W was applied to E1/E2 at condensers sink temperature of 253K/258K. At 18:46 heat loads of 60W/60W were applied to both E1/E2. Loop started about 20 seconds later with 0.4K superheat, and the vapor line temperature (TC8) increased to the CC2 temperature. At such a high power, the loop reached a steady state after a

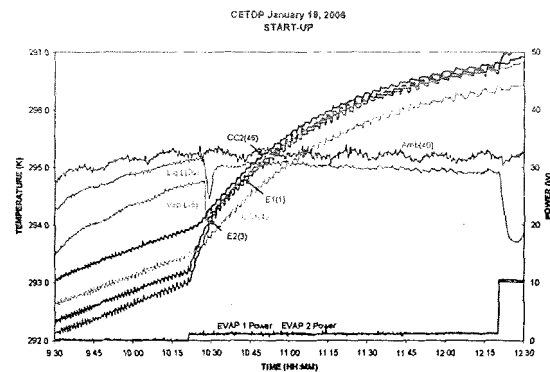


Figure 3. Start-up with E1/E2=1W/1W, C1/C2=293K / 293K.

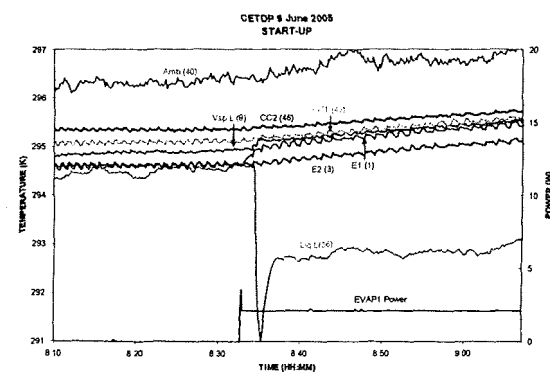


Figure 4. Start-up with E1/E2=2W/0W, C1/C2=273K/ 273K.

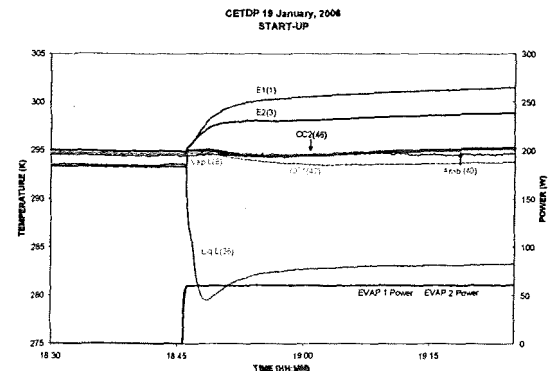


Figure 5. Start-up with E1/E2=60W/60W, C1/C2=253K/258K.

short transient period.

Figure 6 shows the temperature profiles for a start up with 80W to E1 and the condensers sink temperature were maintained at 273K/273K. Loop started almost immediately. In this case E2 had no heat load and worked as a condenser. The inlet temperature (TC39) of E2 was between the liquid line temperature (TC36) and the E1 inlet

temperature (TC38), since the returned liquid to E2 is the combination of the returned liquid from two condensers and that from E1 condenser. In this case CC2 controlled the loop operating temperature.

3-3 High Power Test

When the LHP reaches its capillary limit, vapor will penetrate through the primary wick, leading to a sharp increase of the CC temperature. The thermal conductance of the evaporator will also decrease sharply, resulting in a sharp increase of the temperature difference between the evaporator and the CC. Under most circumstances, the loop will reach a new steady state with the CC reaching a higher temperature. The CC temperature may not return to its previous value as the heat load is reduced because of the residual effect from the vapor penetration into the liquid core. A temperature excursion may result when the applied heat load far exceed the loop's transport limit.

The high power test was conducted following a successful start-up by gradually increasing the heat load in steps until the evaporator capillary limit was exceeded. Figure 7 illustrates the loop temperatures in a capillary limit test where the heat load was applied to E1 only. The C1/C2 sink temperatures were kept at 273K/273K. Since E2 received no heat load, E2 worked as a condenser. Under such a condition where the ambient temperature was higher than the condenser sink temperature, CC2 would always control the loop operating temperature prior to the loop reaching its capillary limit[10-12]. This was experimentally verified in this test for E1/E2 heat loads between 20W/0W and 80W/0W. The capillary limit of E1 was exceeded at 100W/0W as evidenced by four accompanying events[13, 14]. First, the CC1 temperatures (TC42) became uniform and exceeded the CC2 temperatures (TC46), which became subcooled and spread. This suggested that vapor had penetrated through the E1 wick and CC1 began to control the loop operating temperature. Second, immediately following the vapor penetration, cold liquid was pushed from TC38 to TC39 along the liquid line, causing E2 inlet temperature TC39 to drop temporarily. Third, the CC1 temperature increased rapidly for a modest power increase. Fourth, the temperature difference between E1 and CC1 also increased rapidly for a modest power increase due to a decreasing thermal conductance after the vapor penetration. Nevertheless, the loop continued to function at a higher operating temperature. The loop also approached another steady temperature as the heat load further increased to 110W/0W. The loop recovered as the heat load was reduced to 60W/0W. However, the CC1 temperature was about 10K higher than that at 60W/0W prior to the vapor penetration, indicating a residual effect from an

earlier vapor penetration.

Figure 8 shows the loop temperatures in a capillary limit test where an even heat load was applied to both evaporators. The C1/C2 sink temperatures

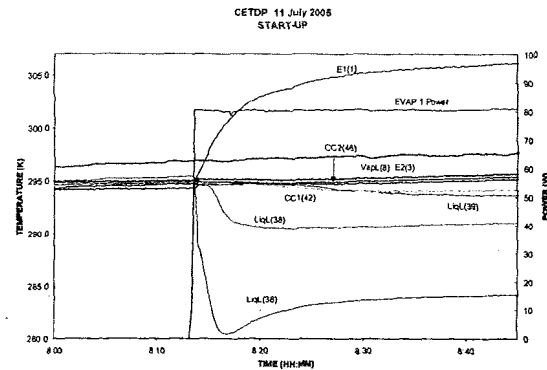


Figure 6. Start-up with E1/E2=80W/0W, C1/C2=273K/273K.

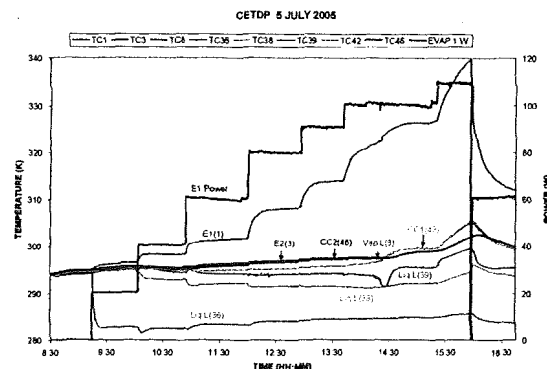


Figure 7. Figure 10 Temperature Profiles During a High Power Test with Heat Load to E1 at 273K Sink

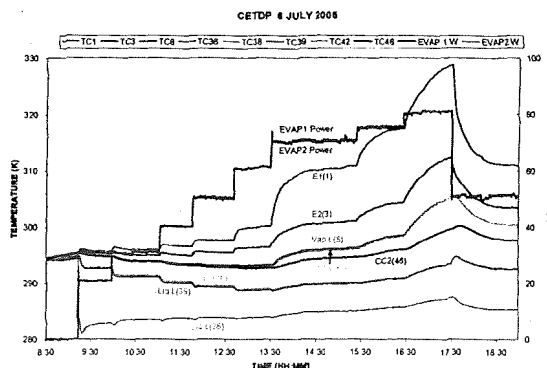


Figure 8. Temperature Profiles During a High Power Test with Heat Load to Both Evaporators at 273K Sink

were kept at 273K/273K. Throughout the test, E1 temperature was always higher than E2 temperature.

The evaporator temperatures began to rise rapidly at 70W/70W for a modest power increase. CC1 temperature also rose and began to control the loop operating temperature. After capillary limit was exceeded at the given operating temperature, however, the loop continued to operate steadily at higher and higher operating temperatures with 75W/75W and 80W/80W. When the heat load was reduced to 50W/50W, the loop recovered from a dry-out. However, the CC1 and CC2 temperatures were 12K and 9K higher than that at 50W/50W prior to the vapor penetration, indicating a residual effect from an earlier vapor penetration.

3-4 Low Power Test

The flow circulation in an LHP is very slow at low powers, and is near stagnation at extreme low powers. The low heat load represents another challenge on the LHP operation.

Figure 9 shows that the loop operated at 1W/1W for first two and a half hours, and 10W/10W for two hours, and then 1W/1W again for four and a half hours. Even at these low powers, the loop operated properly as evidenced by the fact that the liquid line temperature (TC36) varied with the heat load. CC2 controlled the loop operating temperature throughout the test. When heat load increased to 10W/10W, CC2 temperature did not increase. This was because the mass flow rate increased with heat load and the returning liquid provided enough subcooling to compensate for the higher heat leak from the evaporators to CCs. When the heat load was reduced to 1W/1W again, the CC2 temperature was about 3K higher than that of previous 1W/1W. This was caused by a steady increase of the ambient temperature from 296K to 298K over the same period. At heat load of 1W/1W, the CC temperature was mainly a function of the ambient temperature.

3-5 Power Cycle Test

The power cycle test was performed by imposing a sudden, large step change in the evaporator heat load. The purpose of this test was to verify that the LHP could adapt to a rapid change in the heat load, especially during the power step down. Figure 10 shows the temperature profiles during a power cycle of 80W/0W, 60W/20W, 40W/40W, 20W/60W, 0W/80W, and 5W/80W. The condenser sink temperature was 273K/273K.

The CC temperature varied with the heat load. The CC which governs the loop operating temperature switched from CC2 to CC1 as power switched from 40W/40W to 20W/60W. An evaporator which did not receive heat load worked as a condenser as evidenced by the inlet temperature being near the saturation temperature. For example, at 0W/80W, E1 worked as a condenser, after that when the heat

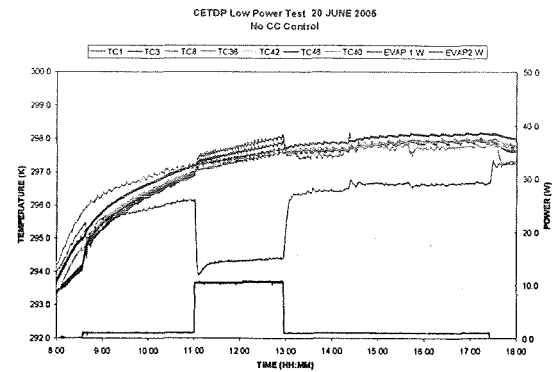


Figure 9 Temperature Profile during a Low Power Test

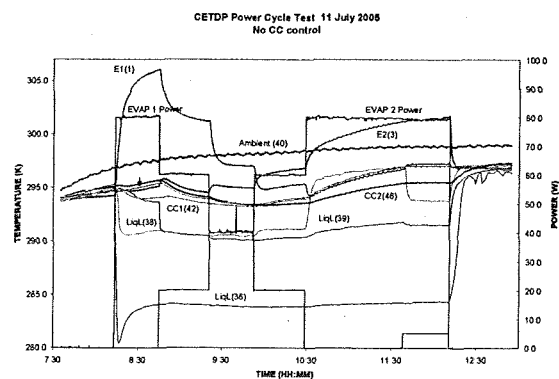


Figure 10 Power Cycle Test of 2.5W/25W/2.5W at Condenser Sink of 273K

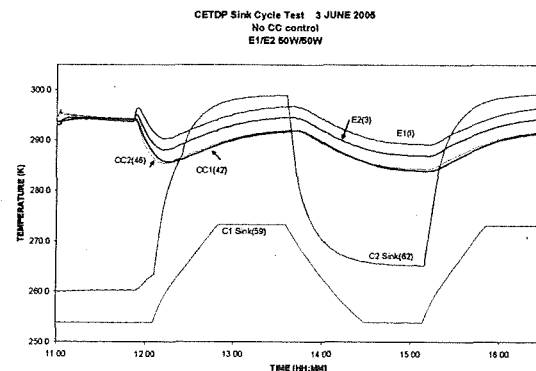


Figure 11 Sink Temperature Cycle Test at 50W

load was at 5W/80W, E1 worked as a normal evaporator as evidenced by a decrease of the inlet temperature (TC38).

3-6 Sink Temperature Cycle Test

The sink temperature cycle test was conducted by imposing a sudden and large change in the condenser sink temperature. The purpose of this test was to verify that the LHP could adapt to a

rapid sink temperature change. Figure 11 shows the temperature profile in a sink temperature cycle test where the evaporator heat load was kept constant at 50W/50W and the condenser sink temperature varied as follows: 253K/260K, 273K/298K, 253K/265K, and 273K/298K. At 11:52, the heat load was increased from 5W/5W to 50W/50W. The loop operating temperature varied with the sink temperature as expected.

4. SUMMARY

Extensive tests of a miniature loop heat pipe with two evaporators having 6.35m O.D. wicks and two condensers were conducted at NASA Goddard Space Flight Center. Tests conducted included start-up, high power, low power, power cycle, and sink temperature cycle. The loop demonstrated robust and reliable operation under various test conditions. The multi-evaporator LHP retains all of the operating characteristics and advantages of the state-of-the-art LHP with a single evaporator, including high heat transport capability, passive and self-regulating operation, no external pumping power, and flexibility in spacecraft design, integration and ground tests.

Experimental data showed that the loop could start with a heat load as low as 2W. The loop operated stably with even and uneven evaporator heat loads, and even and uneven condenser sink temperatures. Heat load sharing between the two evaporators was also successfully demonstrated. The loop had a heat transport capability of 100W to 140W, and could recover from a dry-out by reducing the heat load to evaporators. Low power test results showed the loop could work stably even at 1W/1W. Excellent adaptability of the MLHP to rapid change of power and sink temperature were also demonstrated.

Test results with active control of CC temperature and gravity effects on the loop performance will be published in separate papers.

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